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Precision narrow-angle astrometry of binary stars with the Navy Prototype Optical Interferometer

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ABSTRACT

The Navy Prototype Optical Interferometry (NPOI) group has started an astrometric search for planets in binary star systems based on the idea of using the binary components as position references for one another and looking for deviations from Keplerian motion.

Our search will complement the radial velocity (v_R) searches in three ways. We will observe stars of all spectral types; v_R searches are limited to the FGKM range, where stars exhibit narrow spectral lines. We will search for planets in relatively large orbits (more than about 4 AU) where our method is most sensitive; v_R searches are most sensitive to close-in planets. Finally, we will examine binary star systems, which with a few exceptions have been excluded from v_R surveys.

Our targets are binaries with both components in the interferometric field of view, producing a periodic variation in the fringe visibility (V^2) across the (u, v) plane. Past NPOI results from closer binaries (separations in the tens of mas) show residuals of tens of microarcseconds about the best-fit orbits. The larger separations we are observing produce more V^2 oscillations across the (u, v) plane, offering the possibility of higher precision. We discuss the level of precision in test observations and the steps that will be needed to convert precision into accuracy.

Keywords: Optical interferometry, interferometric imaging, NPOI, binary stars, extrasolar planets

1. MOTIVATION

As Michelson realized long ago, interference phenomena allow us to make extremely precise and accurate measurements. In the realm of stellar optical interferometry, measurements of spectroscopic binary orbits has benefited greatly from this accuracy. The binaries that have been investigated by both spectroscopy and interferometry tend to have separations in the tens of milliarcseconds. Residuals from the interferometric orbits are ≈ 0.1 to a few times 0.01 mas,[1] yielding fractional accuracies of roughly 0.1% to 1%, significantly better than those of the radial velocity (v_R) data. Since deriving stellar masses and orbital parallaxes generally depends on both types of data, these projects have not required higher accuracy of the interferometric measurements.

Binary-star interferometry is capable of considerably higher absolute accuracy. We can improve the accuracy by, e.g., increasing the baseline length or increasing the amount of data. However, the most important area to

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14. ABSTRACT
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work on presently is reducing systematic errors. For the NPOI*,[2] as an example, the most important systematic effect in measuring binary separations is that the effective wavelengths of our spectrometer channels differ from the nominal wavelengths, at levels we believe to be $< 0.5\%$.

We have started a program with the NPOI to develop high-accuracy binary-star astrometry in order to search for planets orbiting one of the components. The evidence for such planets will be the reflex motion of the parent star, as evidenced by variations from Keplerian motion in the binary orbit. Lane & Muterspaugh[3] have begun a similar program using the Palomar Testbed Interferometer (PTI).

The idea of using the reflex motion of a star due to an orbiting planet has been around for a long time, of course. Classical astrometric techniques with modern equipment are capable of accuracies in the 0.1 mas range within small fields, equivalent to the reflex motion of a 10 M_{J} planet orbiting an 0.5 $M_{\odot}$ star in a 10 year (3.7 AU) orbit seen from a distance of 80 pc.

Optical interferometry in binaries can improve on this performance for several reasons. Foremost is that the binary components are seen through the same isoplanatic patch, removing the worst of the atmospheric effects. Second, the resolution of an interferometer is an order of magnitude or more better than the theoretical resolution of current single telescopes. The final reason is simplicity (if that term can be applied to interferometry): a long-baseline interferometric observation involves measuring the interference on a few baselines, while observations with a filled aperture, e.g., speckle interferometry, are equivalent to using $\approx 0.5(d/r_0)^2$ baselines, where d is the telescope diameter and r_0 is the Fried parameter.

Extrasolar planet searches of this kind are complementary to the v_{R} searches in several ways. The v_{R} searches are more sensitive to close-in planets that create larger reflex velocities; astrometric searches are sensitive to planets in larger orbits that create larger reflex displacements. The v_{R} searches target G, K, and M stars primarily, because they have sharp spectral lines, while astrometric searches are not limited by the stars' spectral characteristics. Finally, most v_{R} searches have concentrated on single stars, avoiding the complications of multiple sets of spectral lines. Astrometric searches in binary stars will address the question of whether planets can form in such systems.

Two further points are worth noting. The first is that the presence of deviations does not tell us which binary component has the companion. This information must be obtained from other data, such as radial velocities. The second point is that it is not necessary to know the orbit of the binary. Because the period of a stable orbit around one of the components is much shorter than that of the binary itself, finding deviations from the best Keplerian fit to an arc of the binary motion is sufficient for detecting a companion.

2. DIFFERENTIAL BINARY ASTROMETRY

2.1. Basic concepts

In doing differential binary astrometry with an interferometer, one uses the binary components as phase references for one another, taking advantage of the fact that atmospheric effects are nearly common to both. One then derives the separation, as projected onto the interferometer baseline, from the difference in delay between the fringe packets of the components. The width of the fringe packets is the coherence length $\lambda^2/\Delta\lambda$, where $\Delta\lambda$ is the channel width. If the fringe packets are well separated in delay, a supplemental delay line can measure the difference by shuttling between them while the primary delay line keeps the interferometer phased. If the fringe packets overlap, they beat against one another with a frequency in delay space proportional to the separation.

The beating of overlapping fringe packets produces regular variations in the squared fringe visibility $V^2(\mathbf{u})$, where $\mathbf{u}$ is a vector in the (u, v) spatial frequency plane. The V^2 maxima lie on a set of parallel lines, one of them passing through the origin of the (u, v) plane. The angular distance ρ_{bin} between the components is equal to $1/\delta_{uv}$, where δ_{uv} is the separation of the maxima in (u, v) space, while the position angle of the binary is perpendicular to that of the V^2 maxima. Equivalently, the Fourier transform of $V^2(\mathbf{u})$ produces an image of the

*The NPOI, a collaboration between the US Naval Research Laboratory (NRL) and the US Naval Observatory (USNO), in cooperation with the Lowell Observatory, with funding from the Oceanographer of the Navy and the Office of Naval Research, is located on the Lowell Observatory site on Anderson Mesa, AZ.

binary from which the separation vector can be determined. Array geometry, observing wavelength(s), Earth rotation, and stellar position determine the (u, v) points at which V^2 is sampled.

Lane & Muterspaugh[3] observe in the first (non-overlapping fringe packets) mode with PTI; at $\lambda 2.2\ \mu$m with a channel width $\Delta\lambda$ of 0.4 μm, the fringe packet is about 6 waves wide. Stars whose separation projected onto their 110 m baseline is greater than $(\lambda/\Delta\lambda)(\lambda/B)$, or ≈ 25 mas, have separate fringe packets, where B is the baseline length. At the NPOI, we are using the latter mode, using overlapping fringe packets. Our fringe packet width is 33 waves at $\lambda 745$ nm, so the packets overlap when the separations projected onto the baseline are less than ≈ 280 mas for an 18 m baseline or less than ≈ 75 mas for the 67 m baseline.

2.2. Application to the NPOI

The NPOI[2] is a six-element visual-wavelength interferometer located at the Lowell Observatory site in the Coconino National Forest near Flagstaff, Arizona, USA. In its current configuration, it observes with all six elements simultaneously, with baseline lengths ranging from 7 m to 67 m. Up to 11 of the 15 possible baselines, and six of the possible ten independent closure phases, can be observed simultaneously. The array elements are 50 cm siderostats feeding 12 cm apertures. The feed system, including the delay lines, is almost entirely in vacuum to minimize internal seeing and dispersion effects. The backend disperses the light into 16 spectral channels covering $\lambda\lambda 550 - 850$ nm and tracks the group delay of the fringe packet, permitting a high duty cycle of on-fringe data.

Two NPOI fields of view are important for binary astrometry. The first is the diffraction-limited field of view. With 12 cm apertures, the Airy disk is $1.''6$. For separations larger than the Airy disk, the detectors cannot see light from both components simultaneously.

The second is the interferometric field of view, as determined by the baseline lengths and the spectral resolution. The fringe visibility of a star positioned off the phase-tracking center is reduced by the nonzero channel bandwidths in an effect known in radio interferometry as bandwidth smearing. The essential idea is that, on a given baseline $\mathbf{B}$ and in a channel centered at λ_0, the interferometer averages the visibilities along a segment of a ray in the (u, v) plane. The length $\delta\mathbf{u}$ of the ray segment is $(\mathbf{B}_{\rm proj}/\lambda_0)(\Delta\lambda/\lambda_0)$, where $\mathbf{B}_{\rm proj}$ is the projection of the baseline vector onto the sky. If $\rho_{\|}$, the binary separation projected along $\mathbf{B}_{\rm proj}$, exceeds $1/\delta\mathbf{u}$, the V^2 variations due to the binary will be washed out, and no separation measurement can be made.

Other observational constraints include the magnitude limit, currently $\approx 5^{\rm m}$ at I band for the NPOI, and calibration quality, which currently makes it difficult to reach beyond $\Delta m \approx 3$.

3. DETECTING COMPANIONS

3.1. Method and limits

The semimajor axis $a_{\rm reflex}$ of the reflex motion of a star with a planetary companion is given by

$$a_{\rm reflex} = 20\ \mu{\rm as} \left(\frac{D}{50\ {\rm pc}}\right)^{-1} \left(\frac{m_{\rm pl}}{m_{\rm J}}\right) \left(\frac{M_*}{M_\odot}\right)^{-2/3} \left(\frac{P_{\rm pl}}{1\ {\rm yr}}\right)^{2/3}, \qquad (1)$$

where D is the distance to the star, $m_{\rm pl}$ and $m_{\rm J}$ are the masses of the planet and of Jupiter, M_* and $M_\odot$ are the masses of the star and of the sun, and $P_{\rm pl}$ is the period of the planetary orbit.

The planetary orbit must be stable against perturbations by the other binary component. The stability criterion we have chosen here is an extension of a recent analysis by David et al.:[4] for stability on Gyr timescales, the periastron of the binary must be at least 7 times the apastron of the planet, i.e.,

$$a_{\rm bin}(1 - e_{\rm bin}) > 7 a_{\rm pl}(1 + e_{\rm pl}) , \qquad (2)$$

where $a_{\rm pl}$ and $a_{\rm bin}$ are the semimajor axes of the planetary and binary orbits, and $e_{\rm pl}$ and $e_{\rm bin}$ are the orbital eccentricities.

The combination of the stability criterion with the maximum binary separation that the NPOI can measure produces a rough *upper* limit on the reflex motion we can observe for a given $M_{\rm pl}/M_*$ ratio, since the planetary orbit that produces it must fit stably into the largest binary orbit we can observe:

$$a_{\rm reflex,max} = \frac{\lambda_0^2}{\mathbf{B}_{\rm proj}\ \Delta\lambda}\ \frac{1}{7}\ \frac{m_{\rm pl}}{M_*}\ . \tag{3}$$

For example, with $\lambda_0 = 700$ nm and $\Delta\lambda = 20$ nm (the values for channel 7 of the NPOI backend) and a 7 m baseline, $a_{\rm reflex,max}$ ranges from 2 mas for a 10 $M_{\rm J}$ planet orbiting a 0.5 $M_\odot$ star, to 50 μas for a 1 $M_{\rm J}$ planet orbiting a 2 $M_\odot$ star. For a 67 m baseline, $a_{\rm reflex,max}$ ranges from 200 μas to 5 μas for the same combinations of planetary and stellar masses. This limitation holds true when $a_{\rm bin}$ and $\rho_{\rm bin}$ are not too dissimilar. For orbital orientations in which $a_{\rm bin}$ is significantly larger, larger reflex motions can be observed.

3.2. Error terms

It is straightforward to list a number of error terms. The most fundamental is the internal precision of the separation measurement $\sigma_{\rho,{\rm int}}$, given by

$$\sigma_{\rho,{\rm int}}\ \approx\ \text{core of PSF}\ \ \frac{F_2}{F_1}\,\frac{1}{{\rm SNR}_{V^2}}\,\frac{1}{\sqrt{M}}\ \approx\ \frac{\lambda}{B}\,\frac{F_2}{F_1}\,\frac{4}{\sqrt{NV^2}}\,\frac{1}{\sqrt{M}}\ \approx\ 3\ \mu\text{as}\ , \tag{4}$$

where $F_{1,2}$ are the fluxes from the primary and secondary, N is the number of photons per sample per spectrometer channel, and M is the number of samples. The 3 μas estimate is for a $5^{\rm m}$ star with a $F_2/F_1 = 0.5$ and 1000 s of observation with the current NPOI array (PSF ≈ 1.5 mas).

The (u, v) points sampled by a baseline are determined by $\mathbf{B}_{\rm proj}$ and the effective wavelength $\lambda_{\rm eff}$ of observation via $\mathbf{u} = \mathbf{B}_{\rm proj}/\lambda_{\rm eff}$, where $\mathbf{u}$ is the vector position in the (u, v) plane, measured in units of rad^{-1}. Accurate results depend linearly on accurate knowledge of the (u, v) coordinates, and thus of both $\mathbf{B}_{\rm proj}$ and $\lambda_{\rm eff}$. The NPOI baseline coordinates have been shown to be stable to several 10s of μm. With typical baseline lengths in the tens of meters, the fractional error in $\mathbf{B}$ is $\approx 10^{-6}$, and with maximum binary separations of ≈ 100 mas, the error due to baseline uncertainties is well below that due to photon noise (Eq. 4).

The NPOI effective channel wavelengths are considerably less precisely known. We estimate that the repeatability of the spectrometer realignment[†] is $< 0.5\%$, which would produce systematic errors of 500 μas in a 100 mas binary. The stability of the spectrometers between alignments is significantly better. Quantifying this source of systematic error is the most important task in controlling the systematics of NPOI binary astrometry.

Other potential sources of error include variations in atmospheric extinction with zenith angle, which create variations in the effective wavelengths of the spectral channels, color differences between stars, which also affect the effective wavelengths, and variations in baseline lengths from night to night due to slight differences in instrumental alignment. Extinction variations due to Rayleigh scattering will shift the NPOI effective wavelengths by a few parts in 10^6 over a range of zenith angles from $0°$ to $50°$. Effects due to stellar colors can be modeled; for the relatively small channel widths at the NPOI, 0.1 mag accuracy in standard colors will suffice to suppress the errors below those caused by atmospheric extinction. Baseline knowledge, which must be accurate at the level of a few millimeters, can be derived in post processing if care is taken to observe stars well distributed around the sky. A final effect to consider is differential refraction, which spectrally disperses the image of a star at the detector, and does so at an angle that varies with position on the sky. Risley prisms to counteract this effect are being prepared for installation at the NPOI.

4. CANDIDATES

As a result of the considerations discussed in 3.1, the binary systems accessible to this technique are a complicated function of the stellar and planetary masses, their orbital periods, and the distance. See Fig. 1 for one illustration of the constraint, and Table 1 for a summary.

[†]The spectrometer lenslet arrays that are used to feed light into the fibers and thence to the APD detectors are shifted by about a half channel for Hα observations, and are then shifted back for other observing programs. It is the repeatability of these shifts that is at the $< 0.5\%$ level.

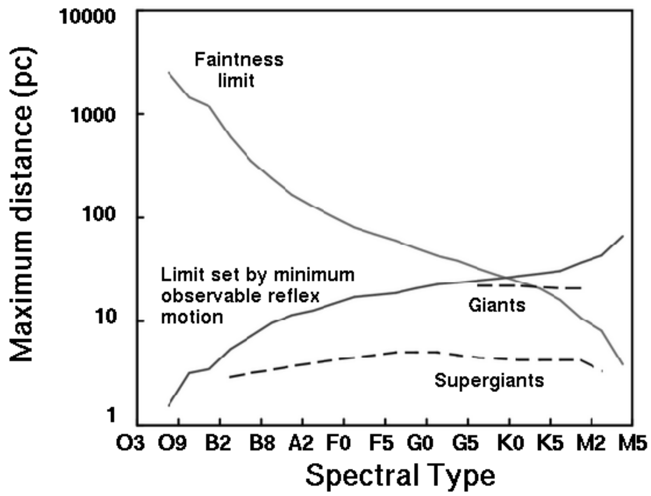

Figure 1. Maximum distance for observing planets in binaries with the NPOI for a particular planetary mass and orbital period, as a function of spectral type. The case shown is that in which the planetary mass and orbital period are $2m_{\rm J}$ and 5 yr, the assumed minimum observable $a_{\rm reflex}$ is 5 μas, and the luminosity limit is $5^{\rm m}$ at I. The solid curves are for main-sequence stars. Reflex motions below both these lines are observable, while motions below only one of the lines are unobservable either because the parent star is so massive that the reflex motion is too small (left) or because the parent star is too faint (right). The dashed curves shows the limit set by reflex motion for giants and supergiants.

Table 1. Rough constraints on an NPOI search for planets in binary systems

Constraint	Value	Comment
Magnitude	$V < 6$	Current NPOI sensitivity
Magnitude difference	$\Delta m < 3$	Keeps V^2 variations detectable
Spectral type	No constraint	No dependence on spectral lines
Maximum separation	$\rho_{\rm bin} < 500$ mas	Component images overlap
Separation precision	$\sigma_{\rho_{\rm bin}} > 3$ μas	Photon noise limit for 1000 s
Planetary orbital size	$a_{\rm pl} < 7a_{\rm bin}$	Stable orbit
Maximum reflex motion	$a_{\rm reflex} < 400$ μas	Keeps $a_{\rm bin}$ within limits

We have compiled a list of candidate systems, using the NPOI magnitude and declination limits given above. Our source catalogs include the Washington Double Star Catalog,[5] the Sixth Orbit Catalog,[6] the Eighth Spectroscopic Binary Catalog,[7] and the Bright Star Catalog.[8] We have found 149 systems in a first cut at the candidate list, and are refining the list as we gather information about magnitude differences and as we estimate orbital parameters from the available data. Of particular interest are binary systems with relatively large orbits ($>$ 10 AU) but whose orbital orientation is such that the separation on the sky is small. In those cases, the effective wavelength uncertainty of the NPOI spectral channels becomes less important.

5. TEST DATA

The first candidate for which we have taken a significant amount of data is β CrB, a speckle and single-line spectroscopic binary with a published period of 10.55 yr.[9] It is also a well-studied Ap star (Morgan et al.[10] give a spectral type of F0p) and magnetic variable, and more to the point for our study, there is some evidence in the $v_{\rm R}$ data for a third body in the system. Radial velocities from 1910–1912 show variations with a period $P = 0.88$ yr[9, 11, 12] and velocity amplitude $K = 1.14$ km s^{-1}, but the velocity amplitude of that orbit had declined to nearly zero by the late 1980s, leading Kamper et al. to suggest that the orbit may now be very nearly in the

plane of the sky.[9] If the third component is real, it orbits the primary and has a mass function of $\approx 5\times10^{-5}M_{\odot}$. However, if the orbital inclination is near 0°, the third component is almost certainly stellar; in that case, the reflex motion of the primary can easily exceed 100 μas, which the NPOI should readily detect.

In order to quantify the internal precision of the data, we have concentrated on our observations of 2003 June 4. The data were reduced and calibrated using the standard NPOI techniques (e.g., Refs. 1 and 13). The amplitude of V^2 variations due to the relatively large binary separation varied as expected with baseline length, with the largest amplitudes appearing on the shortest baselines. Using all the data from this night, we find $(\rho, \theta) = (142.483 \pm 0.007$ mas, $174.^{\circ}1210 \pm 0.^{\circ}0017)$, i.e., an uncertainty of 4 μas in $\rho \sin\theta$, and magnitude differences of 2.3 and 1.8 and V and I bands, respectively. These *internal* uncertainties are consistent with the estimate of Eq. 4. Further tests are under way. We are testing the repeatability of ρ and θ measurements in runs consisting of several nights' observations. We are also assessing the external accuracy with simultaneous NPOI and PTI observations, using the fact that the PTI results do not depend on the effective wavelength of its spectral channels.

6. CONCLUSION

Precision astrometric interferometry in binary star systems is a promising technique for planet searches that complement the radial-velocity techniques that have been so successful. Internal errors of a few microarcseconds are possible if the systematic errors can be controlled. The number of candidate systems is limited by a variety of factors, including instrumental sensitivity and resolution, the interferometric field of view, and the requirement that the planetary orbit be stable. Nevertheless, we have compiled a list of well over 100 candidate systems. Test observations of β CrB with the NPOI demonstrate that internal errors can be held to microarcsecond levels.

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